conf. 790505--14

LIMITATIONS OF THERMOCOUPLES IN TEMPERATURE MEASUREMENTS

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DEPARTMENT OF ENERGY

ABSTRACT

Factors limiting the accuracy of temperature measurements with type K and type S sheathed thermocouple assemblies are discussed. The effect of short-range ordering in Chromel is shown to limit the accuracy of temperature measurements made with type K thermocouple to about 1%. Errors of as much as 150% have been observed in type K thermocouples in magnetic fields at temperatures below the Curie temperature of Alumel. Both positive and negative errors were observed when the orientations of the applied magnetic field, the temperature gradient and the axis of the Alumel wire were such as to produce an emf along the thermocouple wire due to the Nernst-Ettingshausen effect. Drift tests of type K thermocouple assemblies sheathed in stainless steel showed changes in indicated temperature of -13°C after 50 hours at 1100°C, while Inconel sheathed assemblies in the same test showed a change less than 1°C. Base metal sheaths caused large decalibrations in type S thermocouples, whereas with noble metal alloy sheaths type S thermocouples were stable to 1300°C. Errors due to the decrease in electrical in resistance with increasing temperature were investigated. The uncertainties associated with high speed data acquisition systems were analyzed and it is shown that the higher emf output of a type K thermocouple does not result in an increase in accuracy over type S thermocouples over a wide range of temperature.

Introduction

Thermocouples are easily the most widely used temperature sensors in process control systems. The advantages are obvious. Thermocouples are inexpensive, they can be remotely located and the many available types cover a temperature range from about -269 to 3000°C. Because of their wide-spread use in critical control systems and in research at the Oak Ridge National Laboratory, the Instrumentation and Controls Division has maintained programs at ORNL to evaluate the performance of thermocouple materials and sources of error in thermocouple measuring systems. Over the years, since the establishment of the I&C Division, we have accumulated an estimated 300 man-years of experience in thermocouple thermometry, both directly and through our function as a national laboratory by providing advice and consultation to inquiries from inside and outside of the laboratory. In this paper we will discuss several common sources of temperature measurement error and the steps which can be taken to minimize these errors. The seven sources of errors in thermocouple thermometry which we will consider are given in Table 1. We frequently refer to this list as the "Seven Deadly Sins" in thermocouple thermometry.

1. Thermal Shunting

Thermal shunting errors occur because the emplacement or attachment of a thermocouple disturbs the temperature distribution of any object to which it is immersed (See Figure 1). This is because the thermocouple has a finite size and conducts heat away from (or to) the object. In addition the thermocouple loses or gains heat from the surroundings by conduction, convection and radiation. Thus the measuring junction of the thermocouple may be at a different temperature, higher or lower, than the object. In addition, if the object has a low thermal conductivity, the thermocouple can change the temperature of the object locally. These temperature differences due to the presence of the thermocouple are called "thermal shunting" errors. The magnitude of the thermal shunting depends on the size of the thermocouple, the thermal conductivities of the sensor and the object, the method of attachment of the sensor, the temperature of the surrounding medium and the heat transfer coefficient of the medium (See Figure 2). In addition, in transient measurements, thermal shunting errors are aggravated.

To minimize thermal shunting errors, the sensor leads should be installed along an isotherm for some distance from the measuring junction.

2. Electrical Shunting and Electrical Leakage

In most applications, thermocouples are installed with ceramic insulators separating the thermocouple wires. Since the electrical conductivity of ceramic insulators increases exponentially with increasing temperature, at high temperatures, the electrical conductivity of even the best electrical insulators becomes great enough to cause appreciable shunting of the

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thermocouple emf. Such "electrical shunting" can cause large temperature measurement errors. Figure 3 illustrates three ways in which low insulation resistance at high temperatures can cause a thermocouple to read either too high or too low. In example 1, a thermocouple inserted into the temperature profile as illustrated will indicate a temperature which is too low because of a loss of emf by leakage through the lowered electrical resistance of the insulator between the thermocouple wires above approximately 1000°C. In example 2, a thermocouple which passes through a zone that is hotter than that of the measuring junction will tend to indicate a temperature that is too high because of the creation of a "virtual junction" in the hottest portion. In example 3, a thermocouple in the presence of a small dc leakage current on the sheath can indicate either too high or too low a temperature, depending on the direction of the current flow. The lowered insulation resistance in the high temperature region will allow a fraction of the current on the sheath to circulate in the thermocouple circuit. Since the two wires on a thermocouple generally have different electrical resistivities (with Chromel and Alumel for example, the ratio of the electrical resistivities is about 2:1), the result is that a net emf is generated in the thermocouple circuit.

To recapitulate, Figure 4 illustrates how shunting and virtual junction errors combine as a thermocouple is inserted through a high-temperature profile. During initial insertion, the temperatures are too low to cause electrical shunting, and the indicated temperatures are correct. Upon further insertion into a region where the temperature is high enough (greater than approximately 1000°C) for shunting to occur, the thermocouple will indicate too low. The thermocouple will continue to indicate too low a temperature until the measuring junction reaches point a, where it will again read correctly because the virtual junction effect. Insertion beyond point "a" will cause the thermocouple to indicate too high a temperature because the virtual junction effect will predominate.

The errors resulting from electrical shunting or electrical leakage can be estimated and interpreted using an analytical model developed by M. J. Roberts and T. G. Kollie of the I&C Division at ORNL.[1]

In this model, the thermocouple is divided into small sections as shown in Figure 5. The sections are cascaded together and, together with a known temperature profile, a solution is obtained which gives a good approximation to the errors caused by either electrical leakage, electrical shunting, or both.

The necessary parameters (resistance per unit length, the Seebeck coefficients, and the conductances per unit length) for the model were all determined experimentally at several temperatures. Furthermore, the experiment was conducted in such a way as to provide a check on the model. In a comparison of the calculated and measured errors resulting from electrical leakage the agreement, better than 10%, is excellent particularly considering that the input parameters were observed to change with time at higher temperatures during the experiments.

3. Calibration Errors

Temperature is hotness, and values of temperature are measures of hotness. To compare values of temperature, it is necessary to construct a scale of temperature, and many different scales are presently in use; i.e., Fahrenheit, Rankine, Centigrade, Celsius, Kelvin, etc. The scale of temperature which has widest usage in scientific and engineering work is the International Practical Temperature Scale of 1968 (IPTS-68)[2] adopted by the International Conference on Weights and Measures. IPTS-68 not only defines values of temperature for selected reproducible fixed points but prescribes standard instruments and methods for realizing the scale. All measurements of temperature should ultimately be referable to the IPTS-68. The calibration of the working thermometers is the means by which this is accomplished.

Table 2 lists the sources of errors in thermocouple calibrations. Most of these are, of course, the same as those for any temperature measurement in thermocouple thermometry. The exception is No. 4. In 1974, the National Bureau of Standards issued Monograph 125, "Thermocouple Reference Tables Based on IPTS-68"[3], which superceded the NBS Circular 561 Table.[4] At the same time a new Type S (Platinum-10% Rhodium vs Platinum) was defined. The composition of the alloy leg as specified to have 10% ±0.05 wt.% rhodium, and in addition the reference for the platinum leg was changed from Pt-27 to Pt-67.* The net result is that there are now two Type S thermocouples; a "nominal", based on the old Circular 561 Tables and an "exact" based on the Monograph 125 Tables. Manufacturer's of thermocouple wire will supply either, but experience in the Metrology Laboratory at ORNL shows that occasionally the thermocouple manufacturer's can get as confused as everyone else and will supply exact for nominal or visa versa. As seen in Figure 6 the difference between the old NBS 561 tables (marked NBS) and the Monograph 125 table can become significant at higher temperatures. It is about 30 microvolts at 1000°C or about 3°C. Many older process instruments employing Type S thermocouples are based on the NBS Circular 561 Tables, so that if a thermocouple on such an instrument were inadvertently replaced by an "exact" thermocouple

*Pt-27 and Pt-67 are NBS standard reference materials for pure platinum. Pt-67 superceded Pt-27 and can be used as a reference thermoelement for thermocouples. NBS Monograph 125 has tables of positive and negative thermoelements vs. Pt-67 for Types S, R, B, J, K and T thermocouples.

the temperatures would be in error by the amounts indicated in Figure 6. The only reliable way to determine if a thermocouple is "nominal" or "exact" is by accurate calibration against a know standard.

4. Decalibration Errors

Introduction - The calibration of a thermocouple establishes a functional relationship between the emf output of the thermocouple and the temperature of the measuring junction. This will be referred to as the "Temperature-Emf Relationship" (TER). DEcalibration, results from changes of the TER with time at temperature and is usually a function of position. If homogeneity of the thermocouple is destroyed, then the TER becomes dependent on the location of the decalibrated or inhomogeneous portion of the thermocouple with respect to temperature gradients. As a result, REcalibration is usually not possible.

Decalibration can be caused by changes in the metallurgical state of the thermocouple materials, or by changes in the composition of the thermoelements. The rate and extent of these changes depend on factors such as the temperature, the composition of the thermoelements, the composition of the surrounding materials (insulators, protective sheaths, gases) and on the sizes of the thermocouple wires.

The Order-Disorder Effect in Type K - Kollie, et al.[5] have reviewed the order-disorder phenomenon in Chromel and its effect on the emf output of Type K thermocouple. Some of the pertinent points are: between 200 and 600°C, the nickel and chromium atoms in Chromel tend to occupy specific sites in the crystal lattice (the ordered state); above approximately 600°C, the atoms are distributed randomly among the lattice sites (the disordered state); the change from the ordered to the disordered state or visa versa is completely reversible; the rate and extent of the formation of the ordered state is both time and temperature dependent; and the temperature measurement errors caused by the order-disorder transformation approaches 1% of the measured temperature between 0 and 600°C.

The net result of the order-disorder transformation on temperature measurements made with Type K thermocouples is illustrated by Figure 7. The initial calibration of an annealed thermocouple, curve "A", lies within the 3/8% ISA tolerance limit for special grade Chromel-Alumel, but data taken on cooling lies well outside this limit. The calibration curve for a thermocouple which was "pre-ordered" at 482°C is shown by curve "B", and the hysteresis observed on cooling was much less than that for the annealed thermocouple. When the thermocouples are shifted in the furnace and recalibrated, however, new calibration curves result.

Decalibration by Compositional Changes in Type K - Numberous investigators have studied the decalibration of Type K thermocouples in air. Burley[6], in one of the more recent studies, investigated the decalibration of bare wire Type K thermocouples in air at temperatures to 1000°C for times up to 3000 h. For Chromel-Alumel pairs from four different sources, the changes in the emf output of these thermocouples is caused by changes in both the Chromel element and the Alumel element. At 600 and 800°C, the changes in Chromel predominate, while at 1000°C, the changes in the Alumel element cause a major fraction of the change in the emf output of these thermocouples.

The results of our investigation on small diameter (0.5 mm/0.020 in.) sheathed thermocouples have shown much more rapid and extensive decalibrations. This is mainly due to differences in the sizes of the thermoelements (Burley used 3.3 mm diameter wires) and our use of sheathed thermocouples. The presence of a sheath has been shown to contribute to the decalibration both in being a source of impurities which contaminate the thermoelements and in limiting the supply fo oxygen needed to passivate the surface of the thermoelement wires[7] (See Figure 8).

One of the features of the Chromel-Alumel thermocouple which has lead to its wide use in its excellent resistance to oxidation at high temperatures in air. The partial pressure of oxygen inside the sealed sheath is reduc_ substantially when oxidation of the wires and sheath occurs at high temperatures. This being the case, the protective film of oxides on the surfaces of the thermocouple wires cannot be formed and high temperature decalibrations proceed rapidly, particularly in the small wire sizes.

The sorption of H_2O due to hygroscopic tendencies of MgO widely used as an insulatant in sheathed thermocouples can both lower the insulation resistance and provide a source of water vapor where the thermocouple is heated. Lowell[8] and Deadmore have shown that the presence of water vapor enhances the oxidation of Ni-Cr alloys. Water vapor activates the vapor phase transfer of Cr_2O_3, which destroys the protective oxide layer on the alloy.

We have conducted extensive tests on the decalibration in small diameter sheathed thermocouples. Figures 9 and 10 show some results of a 50 h drift test at 1150°C of two Type K thermocouples; one sheathed in Type 304 stainless steel, and the other sheathed in Inconel-600. The temperature indicated by the Type K thermocouple sheathed in stainless steel decreased by approximately 13.5°C during this period. Also shown in Figure 9 are the changes on the individual element of the thermocouple referenced against a platinum standard. It can be seen that the Alumel leg contributes the major part of the decalibration. The Chromel leg remained relatively constant for the first 30 h, then changes occurred to produce the "hump" in the indicated temperature. The Type K thermocouple sheathed in Inconel 600, on the other hand, maintained a constant output over the

50 h period equivalent to about $\pm1^{o}C$. similar effects might be expected to occur in larger sizes of sheathed thermocouples, but over a much longer time, because of the larger wire sizes.

Decalibration of Noble-Metal Thermocouples - The noble-metal thermocouple-sheath combinations listed in Table 3 were calibrated to 1370°C. One thermocouple of each type was cu at positions selected to yield samples which had received different, maximum temperature exposures. The samples were analyzed by an ion microprobe mass analyzer.

The IMMA yielded a host of data which has not been analyzed completely. Several facts are obvious, however, For example, noble-metal thermocouples and base metal sheaths are incompatible. As with the Type K materials, the "as-received" materials showed contamination from the sheath resulting from the manufacturing process. Al, Mg, Cr, Ni, Mn, and Fe were found in small quantities in the section which had not been heated in the calibration experiments. The results were in general similar to those which have been reported for a larger-diameter, Inconel-sheathed, Type S thermocouple[7].

As seen in Figure 11 the 90%Pt-10%Rh sheathed Type S thermocouples showed substantially less decalibration than any other type of thermocouple-sheath combination, and the drift rate at 1305°C was approximately 1 mK/min. The thermocouples showed deviations from the NBS reference tables for Type S thermocouples which were essentially the same as those of high quality, "nominal", bare-wire, Type S standards.

In contrast, the decalibration of the stainless steel sheathed Type S thermocouple shown in Figure 12 was much more severe. Above approximately 800-900°C, the reproducibility was poor, and the total decalibration after heating to 1350°C amounted to more than 80°C after cooling to approximately 600°C.

5. Extension Lead Wire Errors

In precision thermocouple thermometry, the thermocouples wires are brought out directly to a reference junction whose temperature is precisely known and/or controlled. That is, the thermocouple wires extend from the measuring junction to the reference junction in continuous, unbroken lengths without the intervention of extension lead wire or connectors. On a large scale such practice is impractical because; (a) connections to the data acquisition system or process controller must be simple to facilitate the exchange of equipment or thermocouples, (b) the lengths of the small diameter thermocouples must be minimized to reduce the total electrical resistance of the thermocouple circuits; (c) if platinum-10% rhodium versus platinum thermocouples are employed, long lengths of these materials for extension leads would be prohibitively expensive. For these reasons, extension leads are made of alloys which approximately match the thermoelectric properties of the materials from 0 to 200°C. The required match of the thermoelectric properties of the extension lead wire materials to the standard thermocouple materials is given in ANSI MC96.1-1975[9] (see Table 4) in terms of the maximum allowable resultant error in the measured temperature; e.g., Type K (Chromel vs. Alumel) as a $\pm2.2^{o}C$ (0 to 200°C) maximum error and for Type S (90% platinum-10% rhodium vs. platinum) as a $\pm6.7^{o}C$ (0 to 200°C) maximum error.

We have measured the deviations from 0 to 140°C of a random sampling of Type S extension wire obtained from the ORNL Stores, from our Laboratory, and from the I&C Field Shop. The results are shown in Figure 13. These measurements clearly show that the errors due to extension wire may be significant but also calibration of the extension wire can reduce those uncertainties to the order of $\pm0.1^{o}C$ or less. This is also true for Type K extension wires; calibration can reduce the measurement uncertainty to a few tenths of a degree Celsius.

6. Reference Junction Errors

The output of a homogeneous thermocouple, which free from the other errors in Table 1, is determined solely by the difference in temperature between the measuring junction at temperature T and the reference junction at temperature T_o. An error in the reference junction temperature will therefore, directly result in an equivalent error in the measured temperature. For large numbers of thermocouples, the use of a zone box to establish the reference temperature, T_o, is standard practice. These boxes normally are thermostated at 65°C. This temperature should be monitored during an experiment by a thermometer, such as a resistance thermometer, which does not require a reference junciton. The uncertainty due to a lack of uniformity of temperature within the zone box is about $\pm0.2^{o}C$.

7. Data Acquisition Errors

Data acquisition errors or errors due to the measuring instruments, have to be analyzed for the particular installation involved. The errors in measuring the thermal emf of a thermocouple vary from a few millidegrees when high-quality potentiometers are used, to tens of degrees when high speed data loggers are employed. Because of the large number of data acquisition systems available, these errors have not been categorized. In general, data acquisition systems designed for steady state emf measurements, such as potentiometers, are more accurate than data acquisition systems for transient measurements of emf. To paraphrase the Heisenberg uncertainty principle, the product of the speed of data acquisition and the accuracy of data acquisition is approximately constant.

Table 5 is a comparison of the temperature measurement errors of a computer-operated data acquisition system and a high quality potentiometer, both commercial units. The computer system can record 20,000 thermocouple output readings per second with an uncertainty of

±0.25% of full scale (either 10, 20, 40, 80, 160 ..., mV). With a potentiometer, an experienced operator can read one thermocouple output in about 1 min. with an uncertainty of ±(0.01%, + 0.01 V). The computer system errors listed in Table 5 are a factor of 20 to 40 greater than those of the potentiometer for a Type K thermocouple and a factor of 30 to 300 greater for a Type S thermocouple. Thus to gain a factor of 10^6 in data acquisition speed, a factor of at least 20 must be sacrificed in temperature measurement uncertainty, which is a justifiable compromise for many applications.

In Table 5 the potentiometric errors are less for the Type S than for the Type K thermocouple, and the computer system errors for the Type S thermocouple are either equal to or less than those for the Type K thermocouple between 485 and 1035°C. These data demonstrate the fallacy of the often stated superiority of a Type K thermocouple to a Type S thermocouple because the output of the Type K is four times greater than the output of the Type S. This is no longer true with present instrumentation.

One data acquisition error that is difficult to assess is due to nonthermal emfs, often called "noise" or "pick-up", which are either induced on the thermoelements or added to the thermal emf by electrical leakage of the thermocouple insulation. Pick-up errors are common in high temperature thermocouple thermometry and may distort the thermocouple signal so as to render it useless. Errors due to the DC component of the emf pick-up are very difficult to determine; sometimes these errors can be eliminated by turning off all electrical power that might contribute to DC pick-up while the thermocouple emf is measured.

The AC component of the pick-up can be filtered out for steady state and some transient temperature measurements. However, if the thermal emf changes rapidly, filtering may cause the measured emf to lag the true thermal emf of the thermocouple, resulting in temperature measurment errors. For example, a single-pole filter with a roll-off of 3 dB at 2 Hz in series with the thermocouple would cause the thermocouple output to lag -8°C while the thermocouple hot junction experienced a 100°C/sec temperature rise. This filter would also attenuate a 3-mV, peak-to-peak, 60-Hz induced, AC emf by a factor of 30. The result would be that the AC pick-up error would be reduced from ±38°C, unfiltered, to ±9.3°C, filtered (±1.3°C for a Type K thermocouple due to AC emf passed through the filter and 8.0°C due to lag).

Numerical methods have been developed for correcting the transient emf of a thermocouple that is distorted by filtering, by its time response, or by thermal shunting. This technique is known as "deconvolution" of the distorted signal to the true undistorted signal, and requires a mathematical model of the system. A more direct technique, called "digital signal averaging", requires several repeated measurements. Superposition and addition of the repeated measurements allows the unwanted noise to be averaged out. Data smoothing[10] is also effective in reducing errors due to noise or pick-up.

8. Errors Caused by Magnetic Fields

Recently, during at the start-up of a large scale engineering experiment on heat transfer at ORNL, the Type K thermocouples were found to be in error by as much as 150% at 100°C[11]. The behavior shown in Figure 14 is typical of that observed in the heater sheath thermocouples. The indicated temperatures were in error in both positive and negative directions when DC current was run through the electric heaters. When the current was turned off, however, the indicated temperature almost instantly decayed to the correct value.

After considerable study, these large errors were determined to be due to the Ettingshausen-Nernst (EN) effect, which is the thermomagnetic analog of the Hall effect. The conditions necessary for the EN effect are shown in Figure 15. If a magnetic field, B, is normal to a temperature gradient, ∇T, and the plane formed by these two vectors is perpendicular to the axis of a conductor, then an emf is generated along the axis of the conductor given by

$$\epsilon = \int_0^{l_0} (Q \nabla T \times B) \cdot dl$$

where is Q is the EN coefficient and the line intergral is taken along the length, l_0 of the wire. The value of Q, the EN coefficient, is a property of the material of the wire, and from published measurements on Chromel and Alumel, one would predict an effect about 500 times smaller than that observed.

An exploded view of the electric heaters used in the heat transfer experiment is shown in Figure 16. At full power, about 120 KW is generated in the heater by a DC current of 550 A. Each of 49 heaters in the experiment is about 1 cm in diameter and 4 m long with a 3 m heated section. Small diameter Type K thermocouples were imbedded both in the center of the heater as well as swaged in slots in the heater cladding. In the lower right hand corner the vector diagram of Figure 15 is shown for reference.

Since the EN coefficient is related to the magnetic properties of the material, ferromagnetic materials such as Alumel have larger values of Q then non-ferromagnetic materials. Based on this information, it was postulated that if the Alumel was heated above its Curie temperature (approximately 152°C), the errors should be greatly reduced. This was confirmed by experiment, as shown in Figure 17. Other experimental data, confirmed that the errors were caused by the Ettingshausen-Nernst effect: the thermocouples located in the center of the heater rods were unaffected by the heater current, since they are in a field free region at the center of the heater; a laboratory experiment (Figure 18) in which the temperature gradient was generated by a bunsen burner and the magnetic field by permanent magnets produced changes in the indicated temperature (Figure 19) similar to those in Figure 17; and finally the error in indicated temperature could be reversed in the bunsen burner experiment by rotating the magnets 180°.

To be sure, the errors found in this experiment were the result of the particular geometry adopted for the heaters and would not be found in most experimental situations. Finally, since the errors were shown to be negligible above about 150°C, this particular heat transfer experiment was not affected, since the lowest temperature called for in the experimental program was 300°C.

9. Summary

Having considered the sources of errors listed in Table 1, we are now in a position to estimate the bounds of the cumulative effects of these errors on thermocouple thermometry. As an example, for one large scale engineering project at ORNL, the desired temperature measurement uncertainty was specified as ± 8°C below 800°C and ± 15°C above 800°C[12]. Since many of these errors are temperature dependent, they cannot easily be presented in tabular form but are best visualized graphically. Figures 20 and 21 present the results for Type K and Type S thermocouples respectively.

The cumulative effect of the errors due to extension lead wires, the reference zone box and the calibration of a single Type K, Inconel sheathed thermocouple are shown as ± 2°C in the middle of Figure 20. In practice, calibration of each thermocouple (100's) is usually not practical, or in most cases, even desirable. For this reason, thermocouples are normally purchased under specification which include a specification of either "standard" grade (3/4%) or "special" grade (3/8%). More specifically the ISA tolerances for these grades are: 3/4%, ± 2.2°C 0 to 277°C and 0.75% of T from 277 to 1250°C; 3/8%, ± 2.2°C 0 to 277°C and 0.4% of T from 277 to 1250°C. Figure 20 shows the result of adding the ISA allowable tolerance for special grade (3/8%) Type K thermocouple materials to the cumulative error plot.

The ISA tolerance is normally considered a "batch" tolerance. That is the deviation of a particular batch of thermocouple materials should be within this tolerance with reference to the NBS thermocouple reference tables during their heating cycle. The variation between thermocouples made from a particular batch of materials might reasonably be expected to be considerably smaller. Experience in MRDL and in the Instrumentation and Controls Field Shops with calibrations of larger diameter Type K thermocouple assemblies (1 to 3 mm dia), shows that the variations within a particular batch of Type K thermocouple assemblies is normally ± 5°C or less at 1000°C. For reasons previously cited concerning the greater variability of 0.5 mm diameter thermocouple materials, the variations observed within single batches of 0.5 mm diameter thermocouple assemblies is larger. To these errors is then added the contribution due to uncertainties in the measuring system. The thermostated, active filters of the measuring system introduce an error estimated to be ± 1°C.

The data acquisition system for the project contains a high speed (20 kHz) analog-to-digital (A/D) converter for the measurement of thermocouple emf's during fast transient experiments. This A/D converter has an uncertainty of 0.25% of range for ranges of 10, 20, 40, and 80 mV. The steps shown in the cumulative error plot result from the changes in range when the thermocouple output reaches 10 mV at 270°C, 20 mV at 485°C and 40 mV at 867°C.

Shown in Figure ~ is a similar plot of cumulative errors for a Type S thermocouple. The uncertainties due to extensions lead wires (calibrated), the reference box, and calibration contribute a total of ± 1.6°C to 1000°C and increases to ± 2°C between 1000°C to 1400°C, due to an increase in uncertainty in the calibration.

Adding the ISA tolerance for standard grade Type S thermocouples (± 1.5°C or ± 0.25%, whichever is greater) result in the lines marked $\pm 1/4$%. Because of the lower output of the Type S thermocouple, the A/D converter can remain on its most sensitive range to approximately 1035°C and consequently the resultant uncertainty in Temperature is equivalent to ± 2.4°C between 350 and 1035°C. It is believed that even with the lower output of the Type S thermocouple, the additional uncertainty in the DAS due to drift in the active filter amplifiers can be kept to ± 1°C. The increase in uncertainty below approximately 300°C in Figure 21 is caused by the decrease in sensitivity of the Type S thermocouple, but this temperature region is outside the range of temperatures contemplated in these experiments and is, therefore, irrelevant to this discussion.

It should be re-emphasized that the higher output of the Type K thermocouple over that of the Type S, does not result in an improvement in temperature measurement accuracy in a region particularly above 485°C, because the higher output of the Type K thermocouple in this region is offset by the greater uncertainties in the A/D when it is switched automatically from the 20 mV range to the 40 mV range.

The uncertainties due to decalibration must be added to the above uncertainties, which are inherent to the measuring system. With Type K thermocouples, there is an added uncertainty because of the order-disorder transformation. This is indicated by the shaded area bordered by the line K_{o-d} in Figure 20. Since the order-disorder error is always positive, the K_{o-d} line only occurs in the upper half of the plot of cumulative uncertainties. The compositional decalibration errors are indicated by K_{II}. The compositional changes will affect the thermocouples only after exposures to temperatures above approximately 800°C, however, so that uncertainties to the extent indicated by K_{II} in this diagram will occur only after approximately 50 h at 1100°C. Since the high temperature parts of the experimental program will come only at the end of each test, uncertainties of this magnitude will not occur during the major portion of the tests. In this case the error limit in the lower half of the plot will be given by -DAS.

For Type S thermocouples, there is no order-disorder transformation in either Pt or 90%Pt-10%Rh alloys, thus there is no additional uncertainty over that of the (+) DAS curve in the upper half of the error diagram in Figure 21. In the lower half of Figure 21, the errors indicated by curve SI_I for decalibration errors. for the same reasons as cited above, errors of this magnitude would probably not occur unless additional testing were attempted in this temperature region after the completion of testing at approximately 1100°C.

Uncertainties due to thermal shunting, electrical leakage and electrical shunting have not been included in Figures 20 and 21. Accurate evaluation of these errors will have to await the start-up of the experiment, since this requries a knowledge of the actual temperature profiles.

In conclusion, there are at least seven common sources of uncertainty in thermocouple thermometry. Large temperature measurement errors can occur if thermocouples are used without consideration of their physical and chemical properties, particularly at temperatures above 500°C. The magnitudes of many of these errors are unique for each installation. Other errors occur because of poor installation practice. All of these factors must be considered if accurate temperature measurements are to be achieved in thermocouple thermometry.

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ORNL-DWG 78-7641

SEVEN SOURCES OF UNCERTAINTIES IN THERMOCOUPLE THERMOMETRY WHICH MUST BE CONSIDERED ARE:

1. THERMAL SHUNTING
2. ELECTRICAL SHUNTING AND LEAKAGE
3. CALIBRATION ERRORS
4. DECALIBRATION ERRORS
5. EXTENSION LEAD WIRE ERRORS
6. REFERENCE JUNCTION ERRORS
7. MEASUREMENT SYSTEM ERRORS

(THE SEVEN DEADLY SINS)

Table 1

ORNL-DWG 78-7638

ERRORS IN CALIBRATION MAY BE CAUSED BY UNCERTAINTIES IN:

1. REFERENCE TEMPERATURES
2. THERMAL SHUNTING
3. MEASUREMENT OF EMF
4. THE EMF VS TEMPERATURE TABLE OR FUNCTION
5. INHOMOGENEITIES OR COMPOSITION
6. THE METALLURGICAL STATE (ANNEALED, COLD-WORK ETC.)

Table 2

ORNL-DWG 78-7635

TYPE S & TYPE B THERMOCOUPLES SHEATHED WITH

1. 90% PLATINUM-10% RHODIUM
2. 80% PLATINUM-20% RHODIUM
3. TYPE 304 STAINLESS STEEL
4. INCONEL 600

HAVE BEEN STUDIED

Table 3

TABLE 4

TOLERANCES FOR EXTENSION WIRES[a]

Thermocouple Type	Extension Type	Typical Alloys	Temperature Range (°C)	Tolerance (°C)	
				Standard	Special
E	EX	Ni-Cr/Constantan	0 to 204	±1.7	--
J	JX	Fe/Constantan	0 to 204	±2.2	±1.1
K	KX	Ni-Cr/Ni Alloy	0 to 204	±2.2	±1.1
T	TX	Cu/Constantan	-59 to 93	±0.8	±0.4
R,S	SX	Cu/Cu-Ni Alloy B	0 to 204	±6.7	--
B	BX	Cu-Mn Alloy/Cu	0 to 121	±33	--

[a]See Reference 9.

TABLE 5

ERRORS IN TEMPERATURE MEASUREMENT OF TYPE K AND TYPE S THERMOCOUPLES DUE TO DATA ACQUISITION

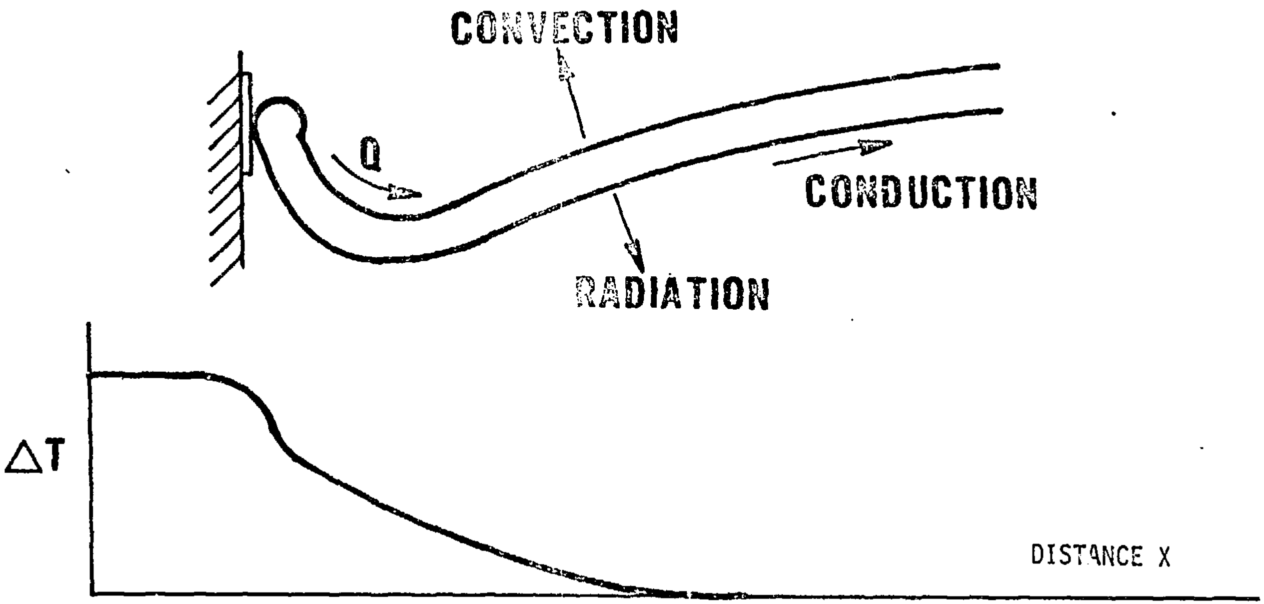
Temperature Range (°C)	EMF range (mV)		Computer System[a] error (°C)		Pot. system[b] error (°C)	
	Type K	Type S	Type K	Type S	Type K	Type S
0-250	10	10	±0.6	±3.2	±0.02	±0.01
250-485	20	10	±1.2	±2.7	±0.03	±0.03
485-965	40	10	±2.4	±2.4	±0.07	±0.06
965-1035	80	10	±5.0	±2.2	±0.11	±0.08
1035-1372	80	20	±5.0	±4.2	±0.12	±0.10
1372-1768	--	20	--	±4.2	--	±0.14

[a]Uncertainty ±0.25% of full scale emf.

[b]Uncertainty ±(0.01%, +0.01 μV) of thermocouple emf.

ORNL-DWG 78-7637

THERMAL SHUNTING RESULTS WHEN A THERMOCOUPLE IS ATTACHED TO AN OBJECT.

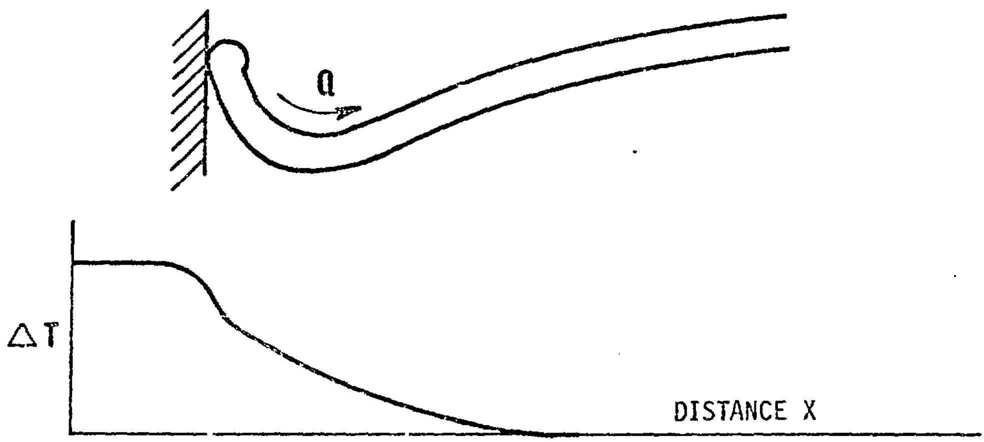


WITH POOR THERMAL CONTACT, THE THERMOCOUPLE JUNCTION WILL NOT ATTAIN THE TEMPERATURE OF THE OBJECT

Figure 1

ORNL-DWG 78-7642

BUT EVEN WITH GOOD THERMAL CONTACT, THE HEAT CONDUCTED AWAY BY THE THERMOCOUPLE WIRES LOWERS THE TEMPERATURE OF THE OBJECT LOCALLY (THE FIN EFFECT).



THERMAL SHUNTING IS AFFECTED BY THE THERMOCOUPLE WIRE SIZE, THE THERMAL CONDUCTIVITIES OF THE OBJECT AND THE THERMOCOUPLE WIRES, THE TEMPERATURE OF THE SURROUNDING MEDIUM AND THE HEAT TRANSFER COEFFICIENT OF THE MEDIUM.

Figure 2

ORNL–DWG 77–14504

AT HIGH TEMPERATURES ELECTRICAL CONDUCTION BETWEEN THE WIRES AND BETWEEN THE WIRES AND SHEATH CAN CAUSE:

1. SHUNTING OF THE THERMOCOUPLE SIGNAL (– ERRORS)
2. CREATION OF VIRTUAL JUNCTIONS (+ ERRORS)
3. ALLOW ELECTRICAL CURRENTS ON THE SHEATH TO LEAK INTO THE THERMO–COUPLE CIRCUITS (± ERRORS)

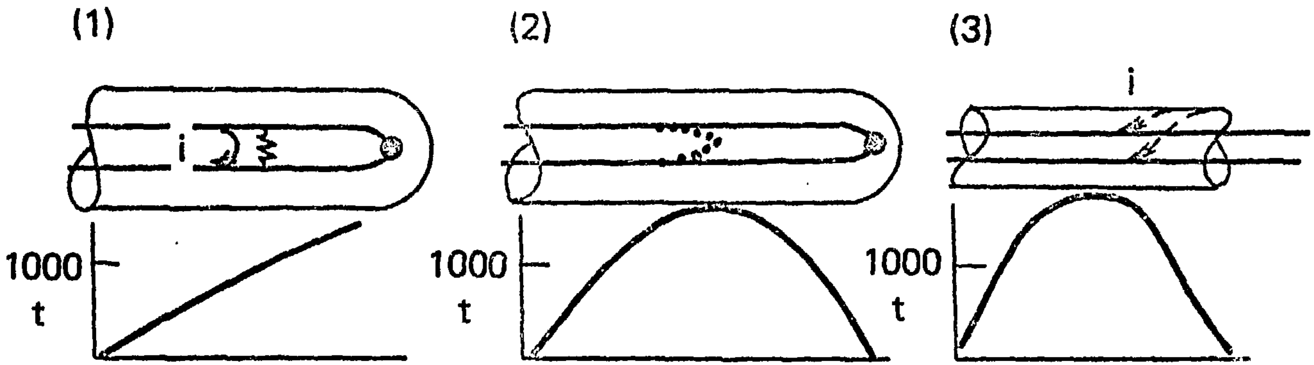


Figure 3

ORNL-DWG 78-7645

BOTH SHUNTING AND VIRTUAL JUNCTION ERRORS COMBINE AS A THERMOCOUPLE IS MOVED THROUGH A HIGH-TEMPERATURE PROFILE:

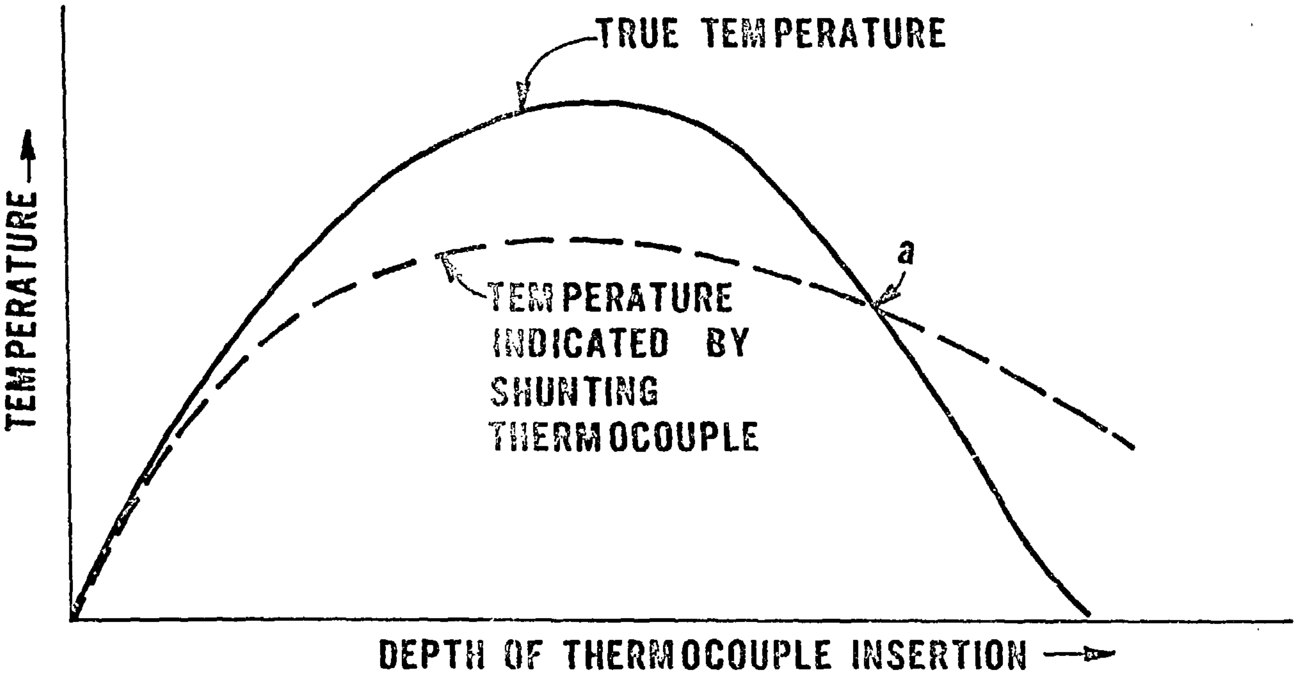


Figure 4

ORNL—DWG 77—14505

ERRORS CAUSED BY ELECTRICAL SHUNTING AND ELECTRICAL LEAKAGE CAN BE CORRECTED AND/OR INTERPRETED BY USING AN ANALYTICAL MODEL DEVELOPED FOR CFTL SMALL DIAMETER THERMOCOUPLES.

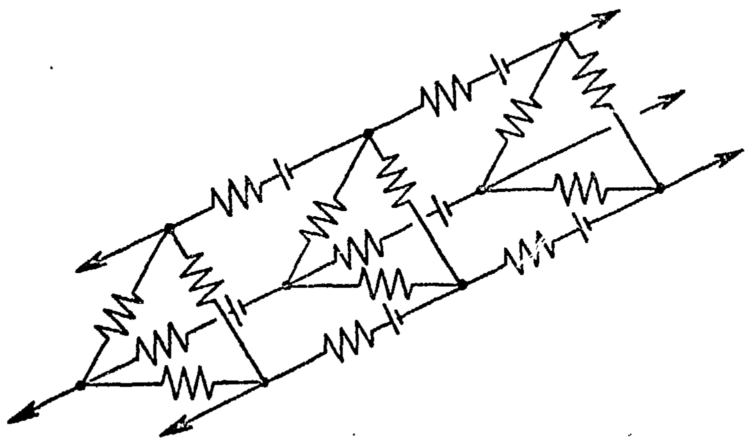


Figure 5

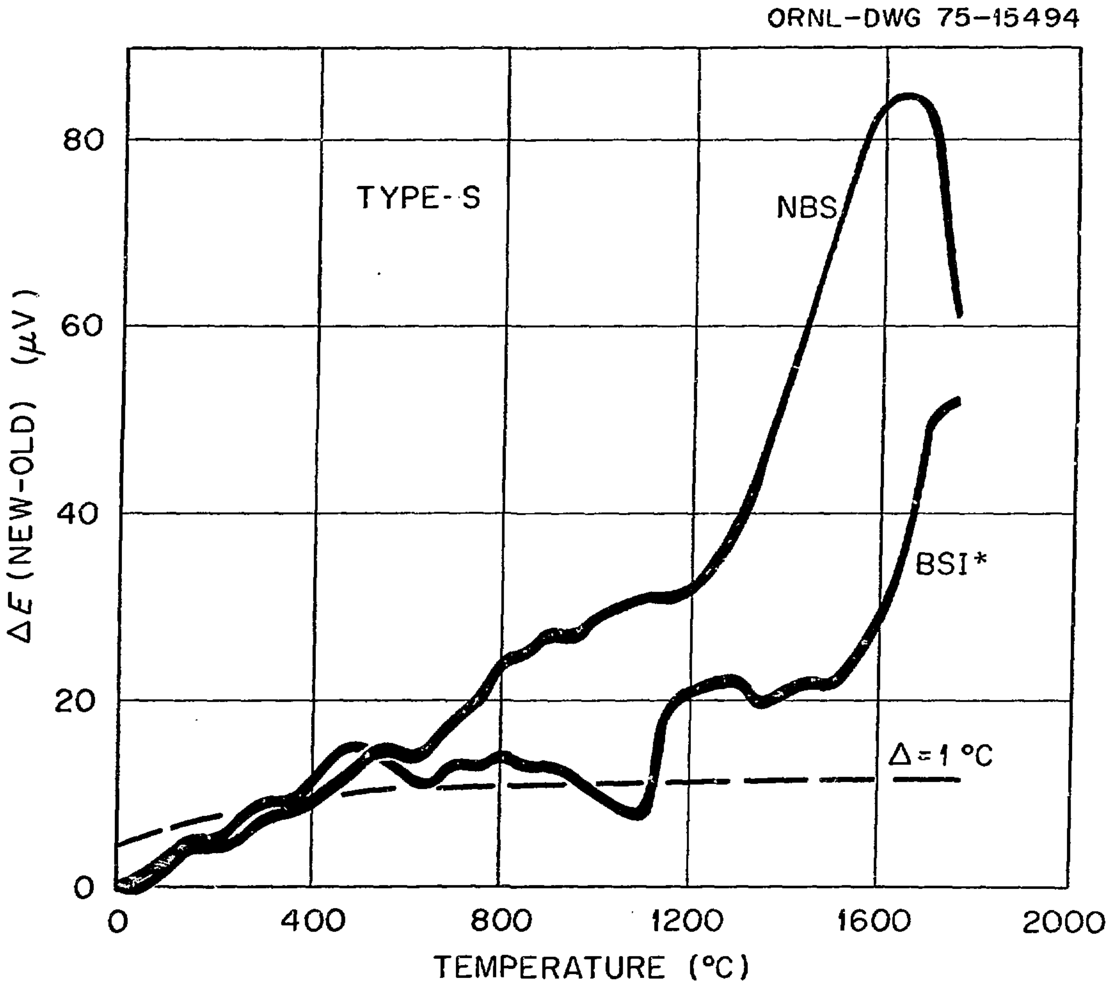


Figure 6. Differences between newly defined "exact" Type S thermocouple defined by NBS Monograph 125 and the older "nominal" Type S thermocouples defined by NBS Circular 561 and the British Standards Institute Tables: B. S. 1825:1952.

ORNL-DWG 78-7643

THE ORDER-DISORDER TRANSFORMATION IN CHROMEL CAN CAUSE UP TO 6-7°C ERROR WITH TYPE K THERMOCOUPLES AT 600°C

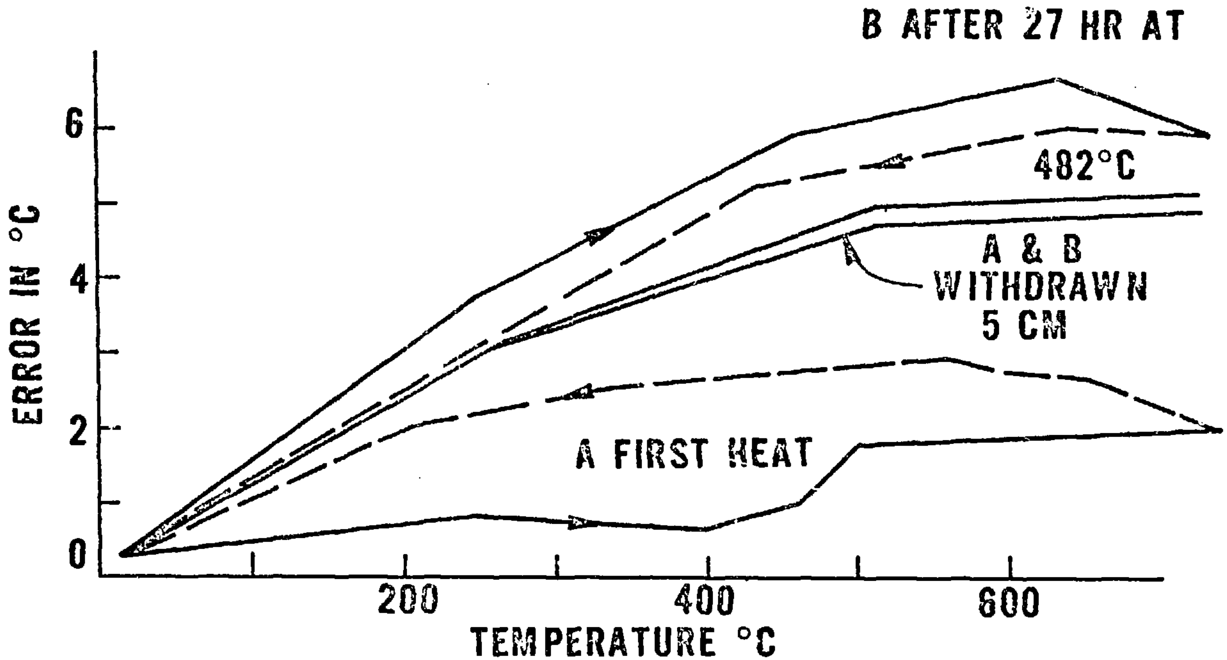
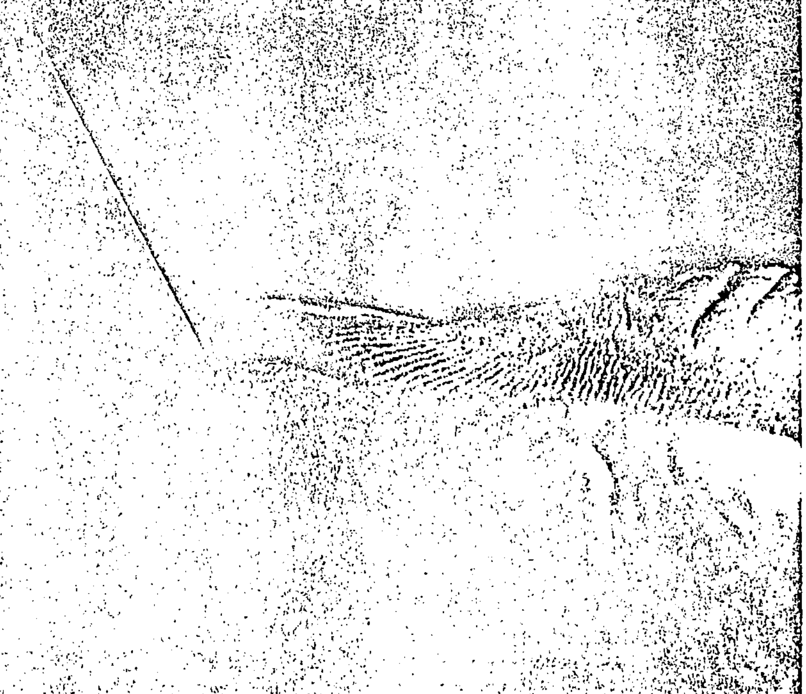


Figure 7

3. WITH THE SMALL SIZES — ESPECIALLY OF THE WIRES



THESE MATERIALS ACT DIFFERENTLY IN THEIR:

1. ELECTRICAL PROPERTIES
2. MECHANICAL PROPERTIES
3. CHEMICAL PROPERTIES

ORNL-DWG 78-7644

LARGE CHANGES WERE OBSERVED IN A STAINLESS STEEL SHEATHED TYPE K THERMOCOUPLE DURING A 50h EXPOSURE AT 1150°C.

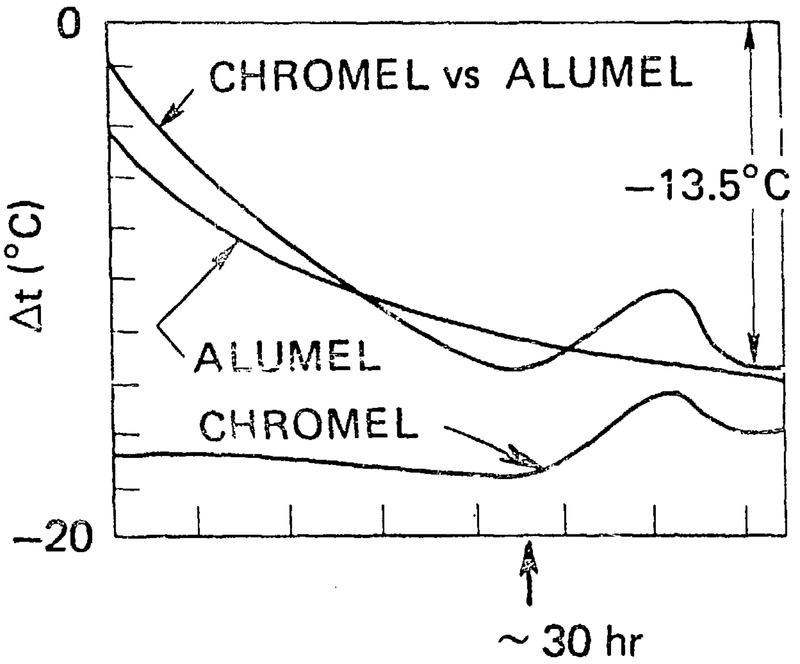


Figure 9

20

ORNL–DWG 77–14509

CHANGES OBSERVED IN TYPE K IN INCONEL–600 ARE MUCH SMALLER

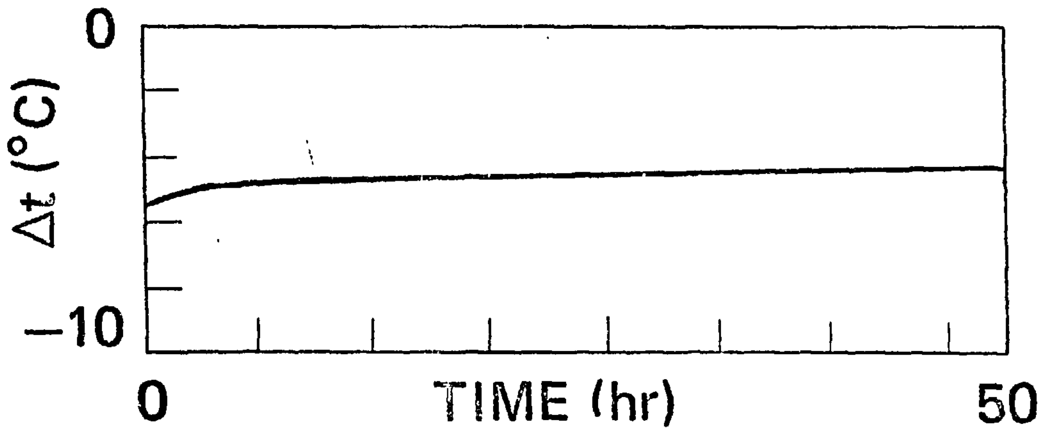


Figure 10

ORNL–DWG 77–14507

THE DRIFT OF THERMOCOUPLES IS STRONGLY DEPENDENT ON THE SHEATH MATERIAL:

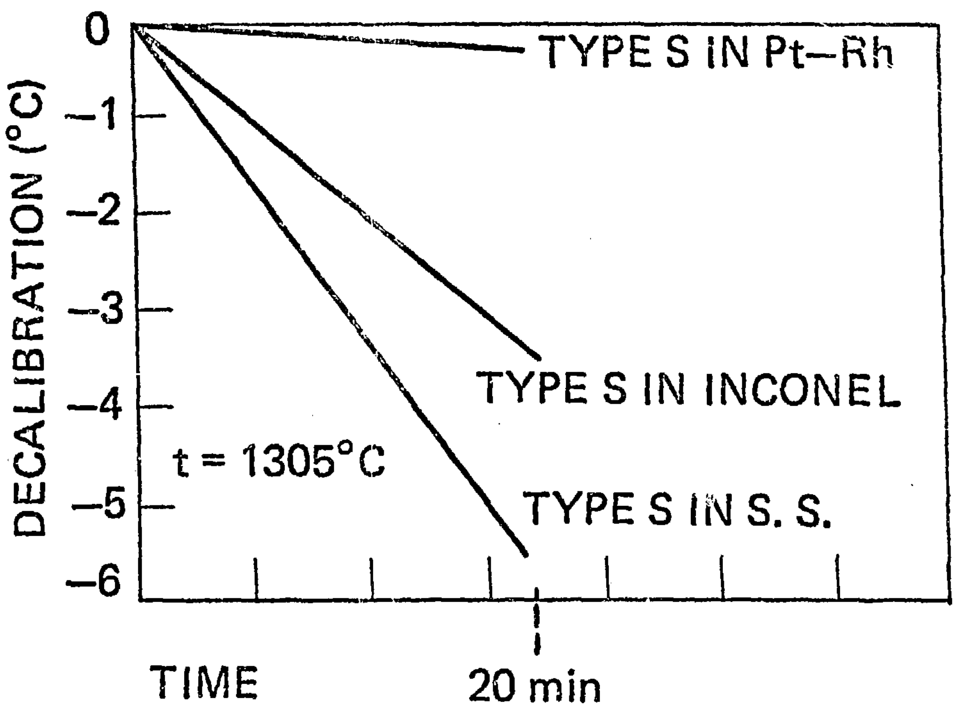


Figure 11

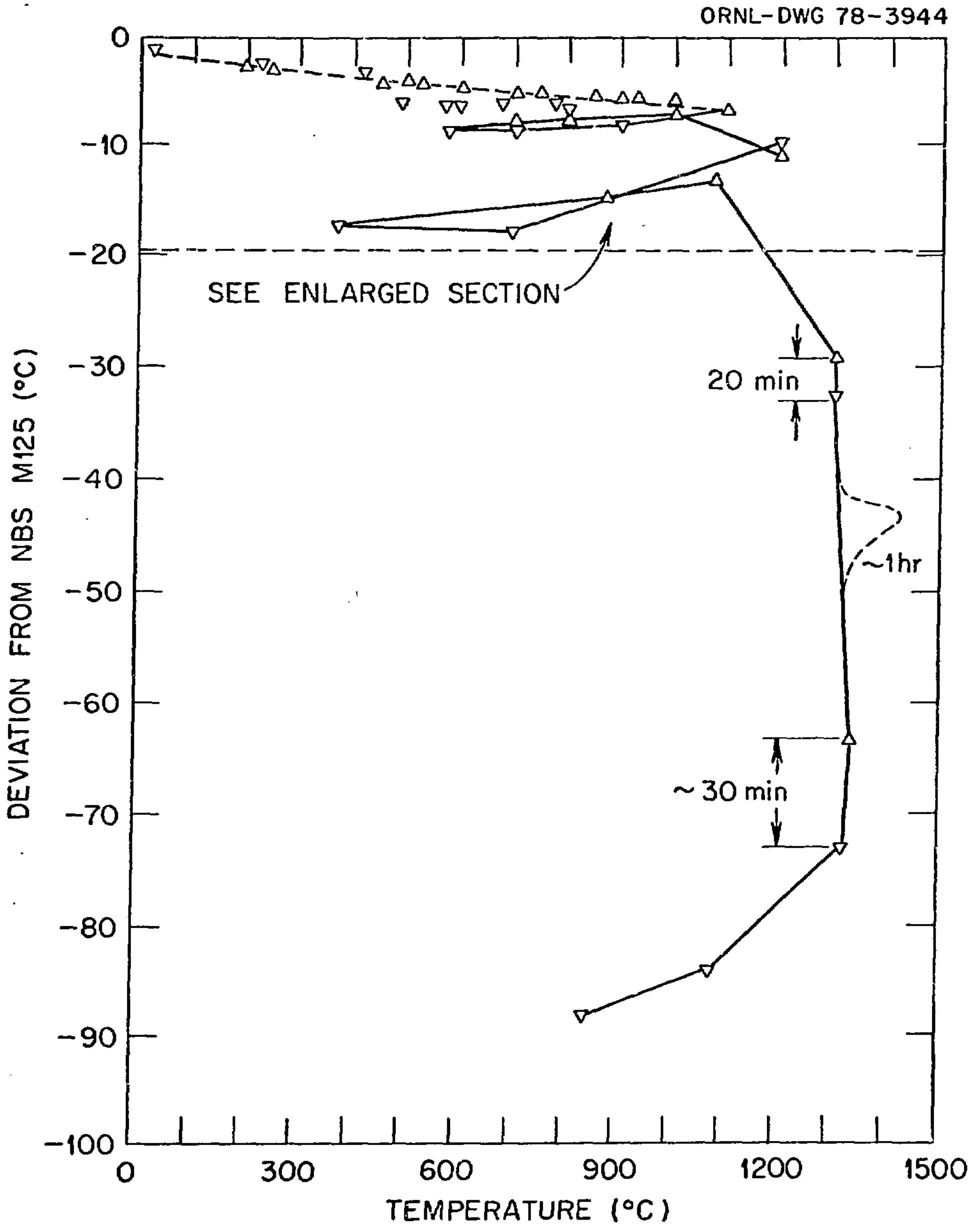


Figure 12. Data from the calibration of a Type 304 stainless steel sheathed, 0.5 mm diameter, Type S thermocouple shows the severe decalibration observed above 900 deg. C.

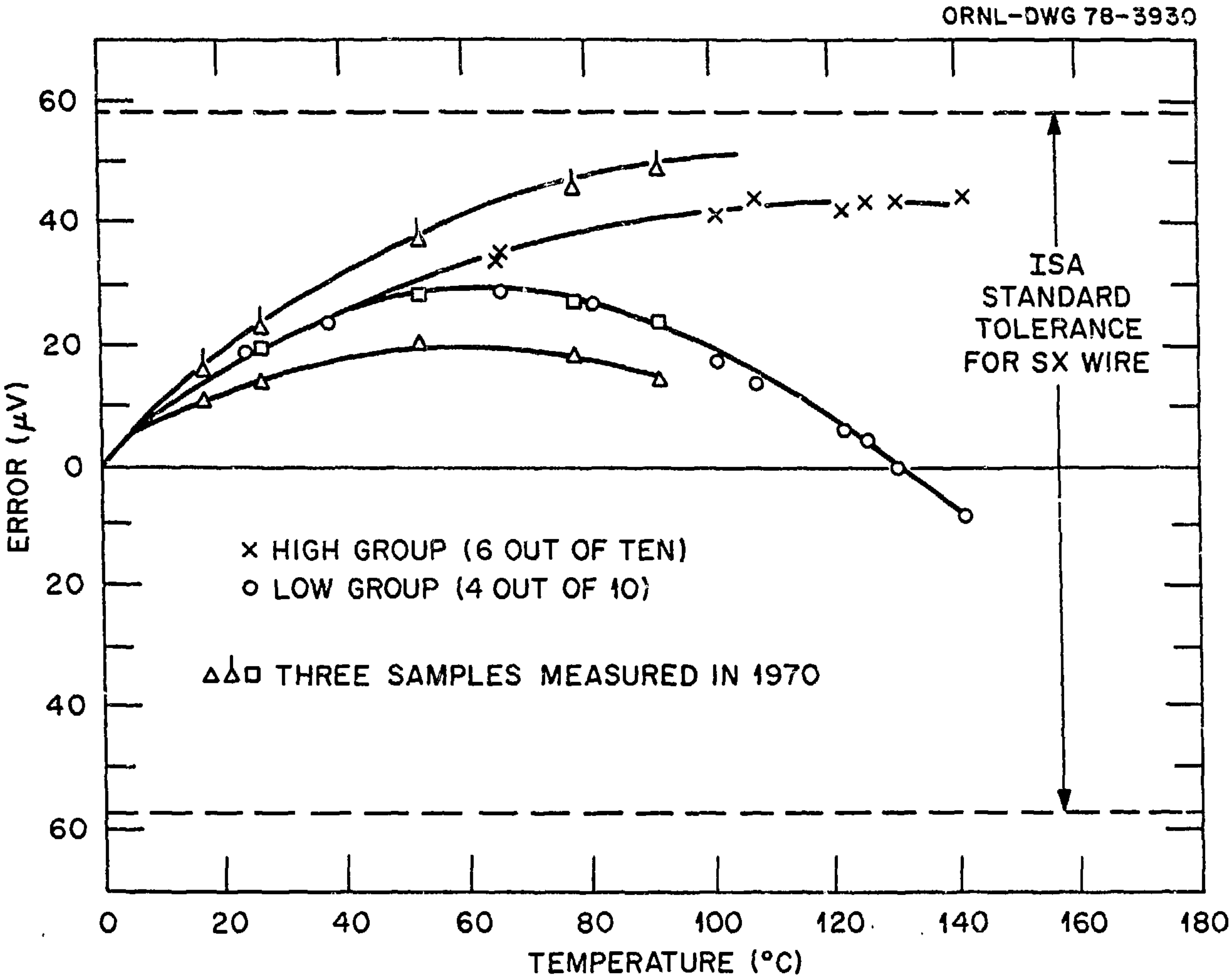


Figure 13. Experimental data from the calibration of various samples of Type S extension lead wire.

ORNL-DWG 76-15493

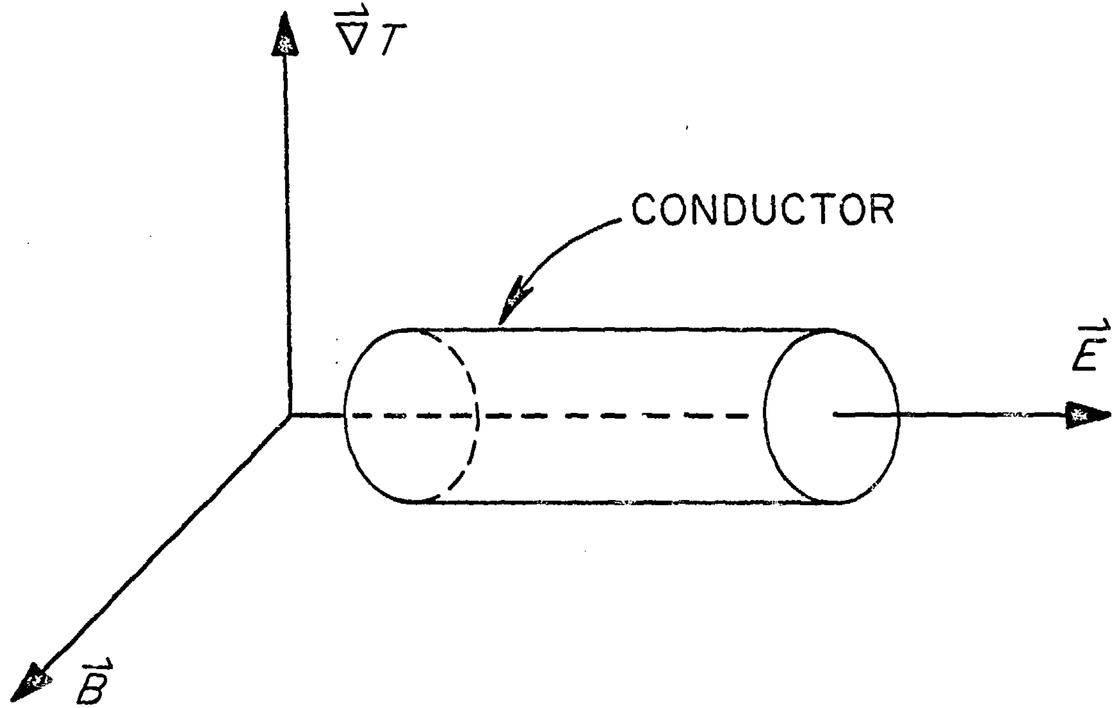


Figure 14. Vector relationship between the temperature gradient, ∇T, the magnetic induction, **B**, and the electric field, **E**, of the Ettingshausen-Nernst effect.

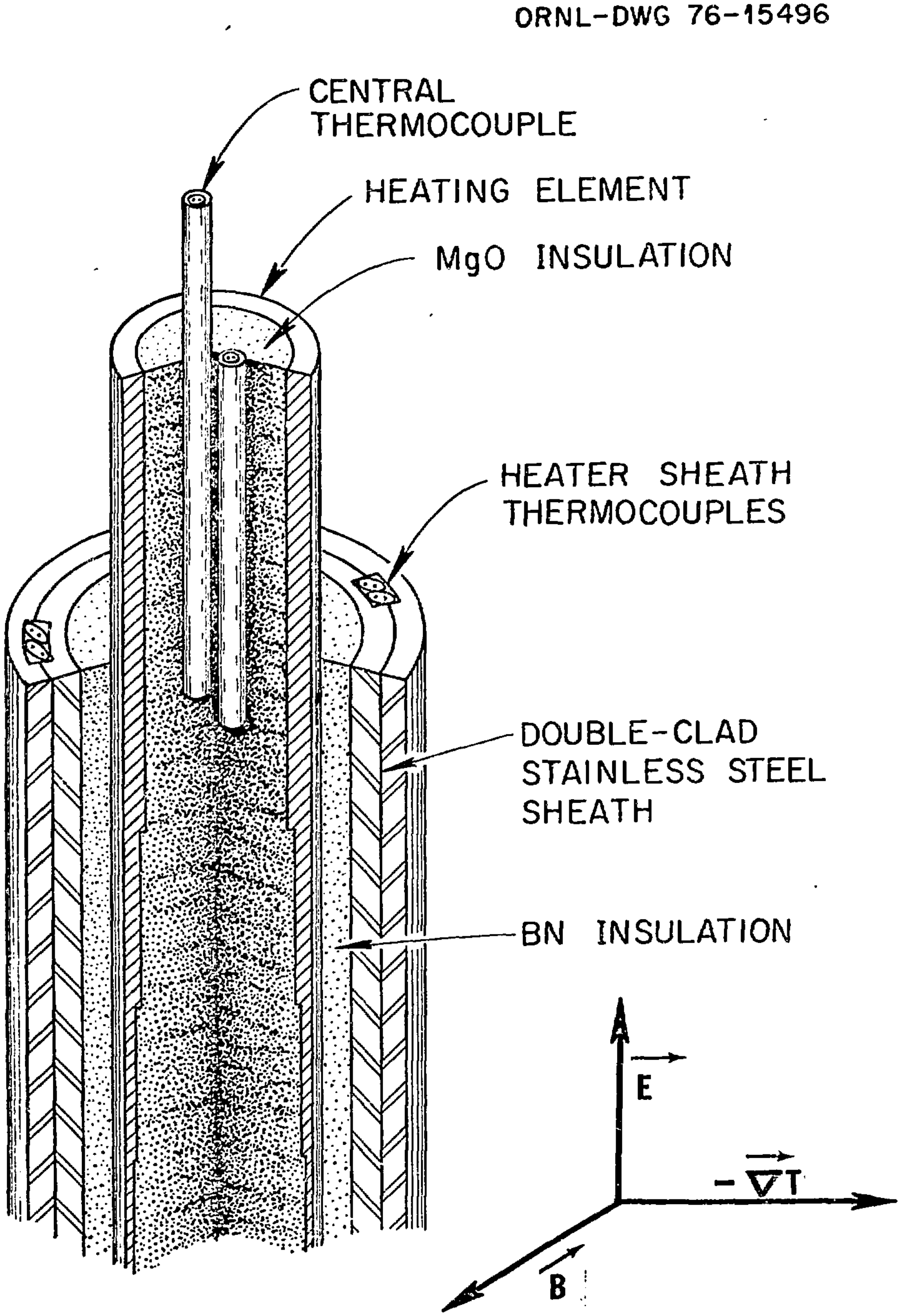


Figure 15. Heater used as a substitute for nuclear fuel rod in nuclear reactor simulation.

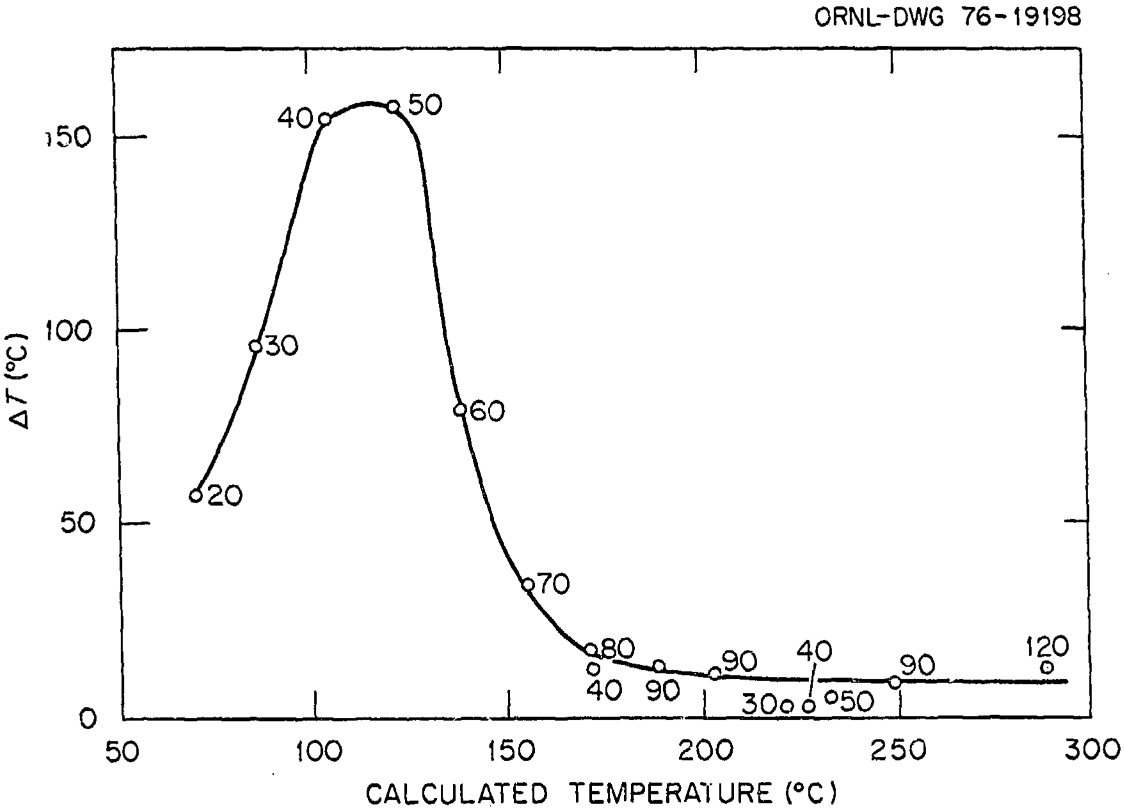


Figure 16. Differences (ΔT) between the calculated temperature and the indicated temperature of one heater-sheath thermocouple of the 49-heater simulator versus the calculated temperature (numbers at each point refer to heater power in kilowatts).

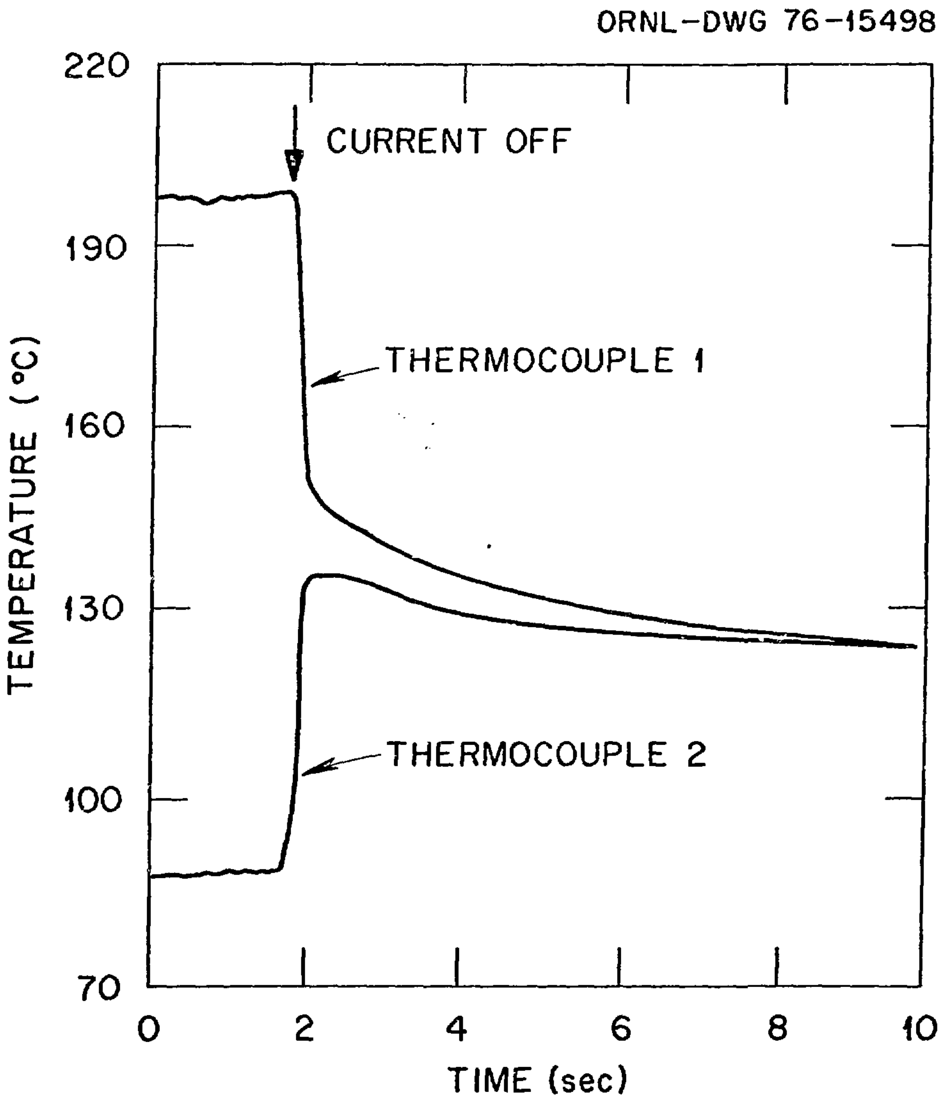


Figure 17. Indicated temperature of two heater-sheath thermocouples as a funciton of time, showing rapid positive and negative changes of indicated temperature at heater-current turnoff.

ORNL-DWG 76-15501

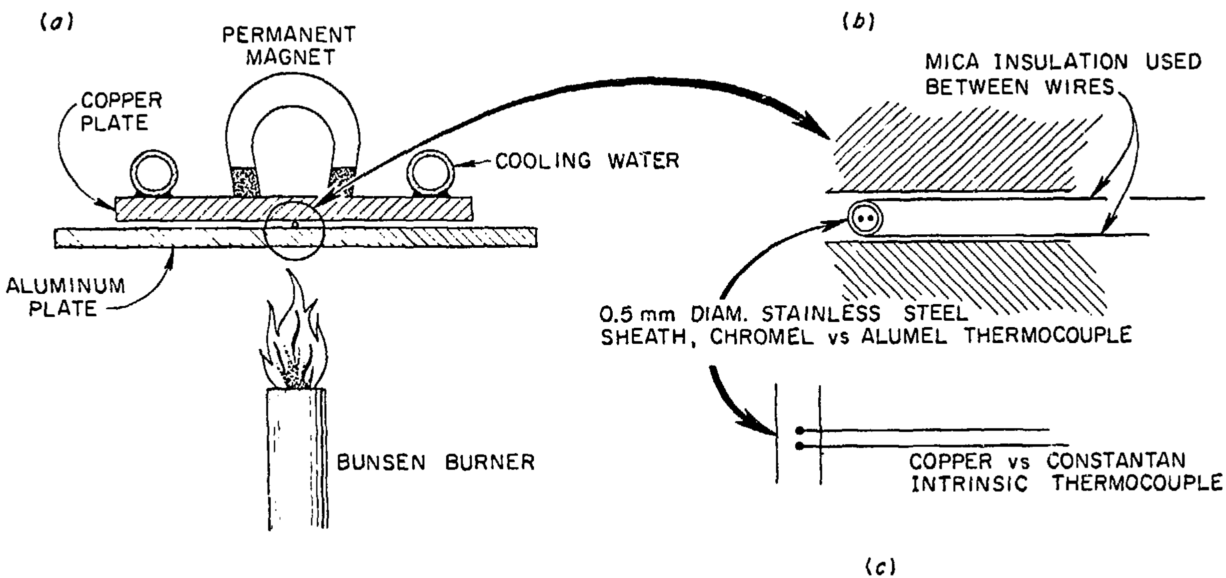


Figure 18. Experimental apparatus used in Bunsen burner tests: (a) apparatus, (b) expanded view of thermocouple placement, and (c) further expanded view of intrinsic thermocouples welded to the top and bottom of sheathed Chromel/Alumel thermocouples to measure ΔT.

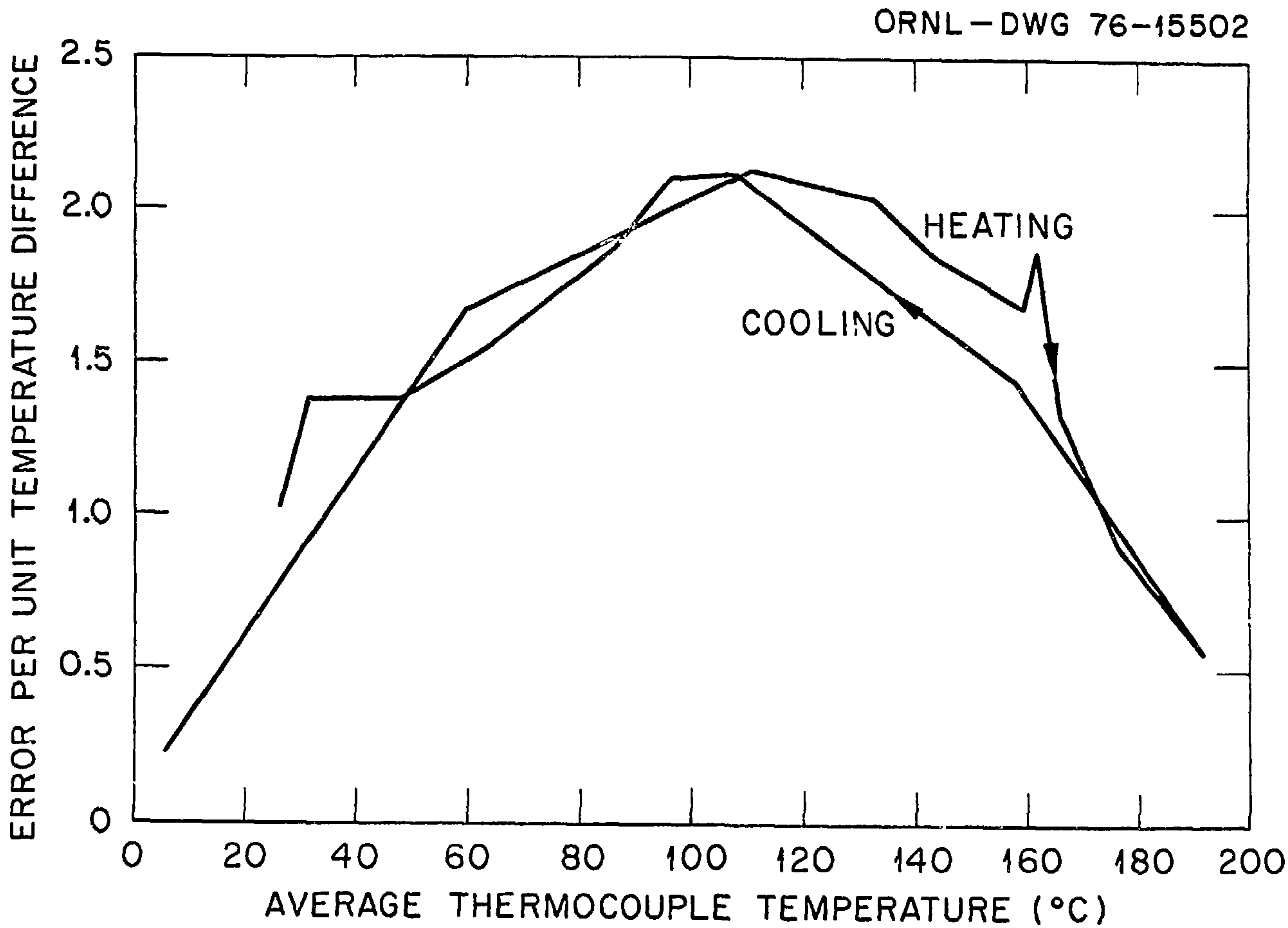


Figure 19. Error per unit temperature difference across test thermocouple versus average temperature of test thermocouple in Bunsen burner test.

ORNL-DWG 78-3665

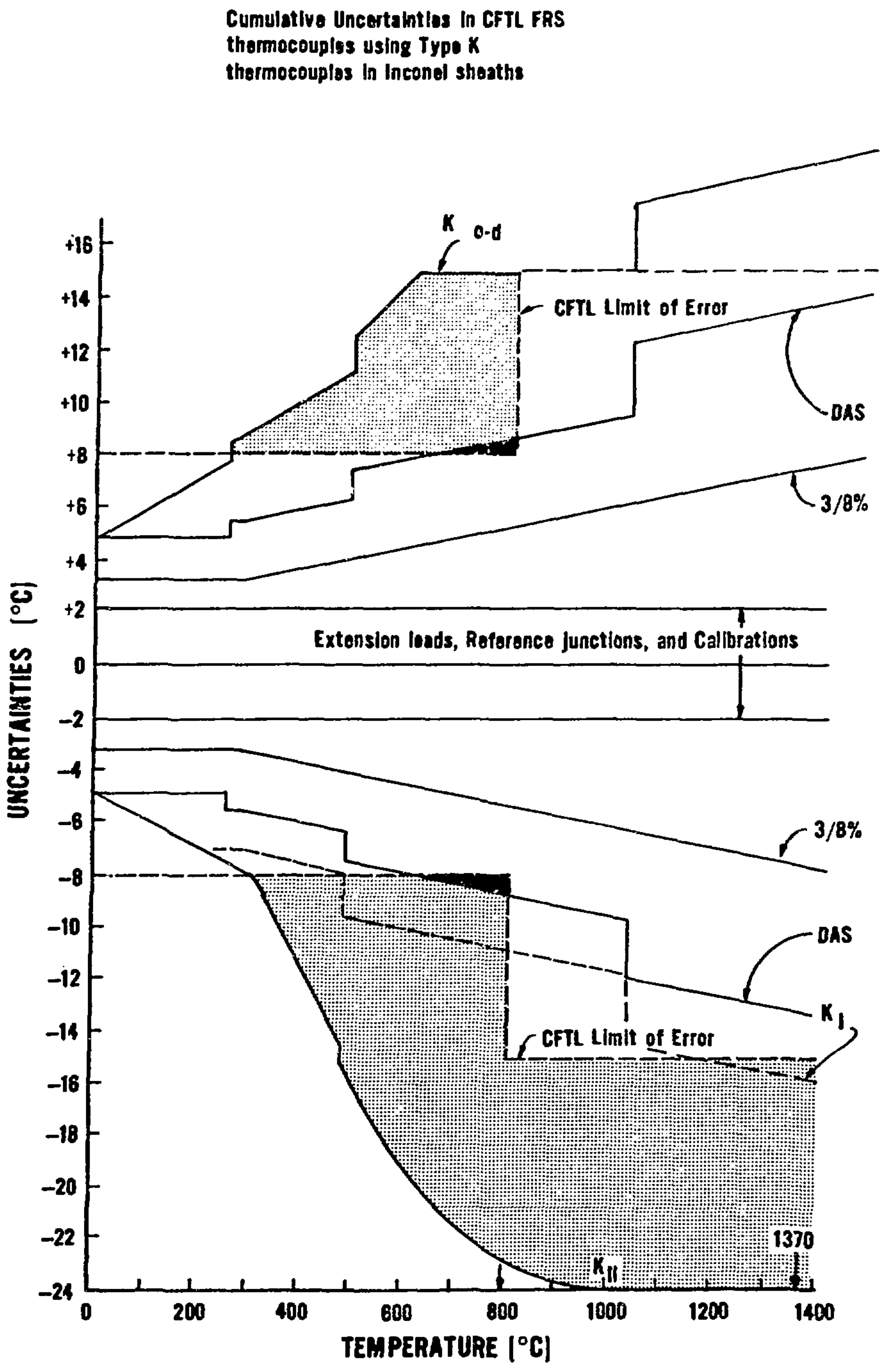


Figure 20.

ORNL-DWG 78-3662

Cumulative Uncertainties in CFTL FRS thermocouple temperature measurements using a Type S thermocouple in a platinum-10% rhodium sheath

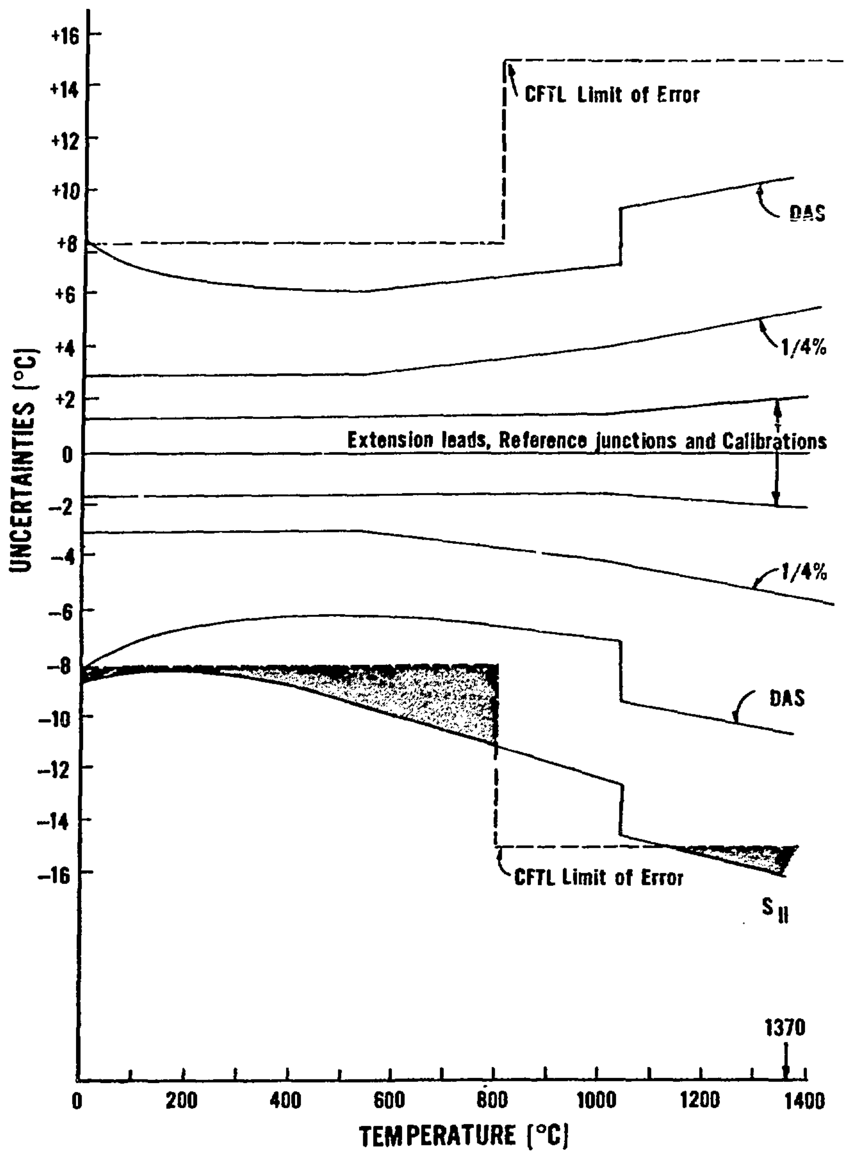


Figure 21.